Biomedical Signal Processing and Control 32 (2017) 57–68

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Stationary versus bifurcation regime for standing wave central pattern generator☆

R. Martin del Campo, E. Jonckheere*

Electrical Engineering Dept., University of Southern California, Los Angeles, CA 90089-2563, United States

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 27 May 2016
Accepted 19 August 2016

Keywords:
Central pattern generator
Surface electromyography
Bifurcation
Coherence
Wavelets
Bootstrapping

ABSTRACT

The purpose of this research is to show that the correlation analysis on surface electromyographic (sEMG) signals that originally confirmed existence of a standing wave central pattern generator (CPG) along the spine are reproducible despite evolution of the entrainment technique, different hardware and data collection protocol. Moreover, as major novelty of the present research, it is shown that this CPG can undergo "bifurcations," here revealed by signal processing extrapolated towards the period-halving dynamical interpretation. The visually intuitive manifestation of the bifurcation is statistically confirmed—using bootstrap analysis—by a shift in the cross power spectral densities, consistently with the standing wave occurring on different subbands of the Daubechies DB3 wavelet decomposition of the sEMG signals.

1. Introduction

1.1. Background

The so-called *spinal wave* [1] is a visually obvious phenomenon during which the spine goes through a rhythmic [2] oscillation elicited by light finger pressure at some sensitized areas of the spine, typically, the neck and the sacrum. As argued in our original work [1], Alf Breig's dural-vertebral attachments [3] close sensory-motor loops in both the neck and the sacrum, creating localized oscillations, which soon propagate along the spine to settle in a standing wave pattern. The crucial features that the movement is rhythmic, that after some initial stimulus it becomes self-sustained and hence has no sensory input, already point to a central pattern generator (CPG), a concept that is still an active area of research [4]. Moreover, as reported in the earlier paper [1], a quadriplegic subject with a C2-C3 injury was able to experience some spinal wave pattern, which indicates that the CPG circuitry is embedded in the spine. Circuit diagrams of the CPG were proposed in [1]. It therefore appears that this movement is, next to gait, another human CPG.

Objectively, the *standing wave* aspect of the CPG was confirmed by observing that the correlation pattern among the cervical, thoracic, lumbar and sacral surface electromyographic (sEMG) signals is consistent with that of a standing wave. This correlation pattern appears most clearly on the D_8 subband of the Daubechies DB3 wavelet decomposition. The choice of the DB3 wavelet decomposition is justified because its mother function mimics the single motor unit action potential, and the D_8 subband appeared the most relevant as the electro-physiological phenomena appear on that subband, while the $D_1, D_2, \ldots$ subbands are composed mostly of high frequency noise [5].

A standing wave oscillation is certainly a manifestation of *coherence* in the neuro-skeletal system. Since the spinal standing wave has its coherence extending from the neck to the sacrum, it is fair to say that this is a phenomenon of *coherence at a distance* [6]. Coherence at a distance between EEG and/or (s)EMG signals is considered to be a sign of the nervous system able to coordinate activities of many muscles towards a specific motion [6]. The additional evidence that we presented in support of this paradigm is the deterioration of coherence in a quadriplegic subject compared with a control subject [1].

1.2. Contribution

The purpose of this paper is threefold. First ("Case Study I"), we show that the early results [1] upon which the CPG hypothesis rests are reproducible. Second ("Case Study II"), we show that the spinal wave CPG, in addition to the classical attributes associated

☆ Research approved by the Institutional Review Board (IRB) of the University of Southern California and supported by the Reorganizational Living Foundation.

* Corresponding author at: 3740 McClintock Avenue, Room EEB 306, Los Angeles, CA 90089-2563, United States.

E-mail addresses: mart737@usc.edu (R. Martin del Campo), jonckhee@usc.edu (E. Jonckheere).

URL: http://eudoxus2.usc.edu (E. Jonckheere).

http://dx.doi.org/10.1016/j.bspc.2016.08.011

with a CPG, can undergo "bifurcations," here understood in a signal processing sense with a view towards the period-halving dynamical interpretation [7]. Finally, another contribution is to show how to deal with signals less than ideal, as those of [1] were.

1.2.1. Reproducibility (Case Study I)

Nearly 10 years separate the data collection upon which [1] is based from the present one. During that time, the entrainment technique evolved to make the movement better controllable (the sEMG signals can be made smooth or bursty at will), the electrode positioning underwent some slight changes while we experienced with different orientation of the differential amplifier input prongs relative to muscle fibers, and the hardware (front-end electronics together with sEMG amplifiers) was upgraded. The software underwent some upgrade as well. Despite these changes and a 10-year span between the two experiments, we show in "Case Study I" that the early results [1] upon which the CPG hypothesis rests are reproducible.

1.2.2. Bifurcation (Case Study II)

In Case Study II, we add another attribute that can be associated with a CPG: the ability to undergo "bifurcations." The early clues that pointed to such phenomena were visually obvious discontinuities in the sEMG signal, as Fig. 5 shows. More formally, here, bifurcation is defined as qualitative structural change; more specifically in the context of the *standing wave* CPG, bifurcation is typically a change in the mode shape, concomitant with a change in the frequency of the coherent oscillations. From a signal processing view point, this amounts to a shift in the cross power spectral density of the signals at a distance, something that we endeavored to confirm with inferential statistics. Another sign of this bifurcation phenomenon is a shift of the coherent oscillations from the D_8 to the D_7 subbands of the DB3 wavelet decomposition. As the difference between D_8 and D_7 is a matter of time scale, this is certainly consistent with the shift of the mean in the cross spectral densities confirmed by statistical tests of hypothesis.

In the topological and qualitative classifications of [8], our definition of "bifurcation" rather matches a "qualitative" trait of [8]. In the dynamical sense, our bifurcation is a period-halving phenomenon [7], so that it has some of the attributes of a topological bifurcation.

Existence of bifurcations should not be that surprising for such a complex system as the human spinal neuro-skeletal system. It simply cannot be expected to oscillate at a single eigenmode and such factors as breathing, even thought processes, have the potential to change the oscillation structural properties. Many such bifurcations on other subjects have already been observed [9,10] using different methods though. In particular, another bifurcation from 1 to 2 mode shape nodes was already confirmed using ARIMA modeling [9] of the SAS statistical package.

1.2.3. Less than ideal signals

In the case the signals are analyzed across a bifurcation, the correlation pattern that reveals coherence cannot be expected to be as crisp as that of the ideal, "textbook" example of [1]. As such, another purpose of Case Study II of the present paper is to assess by how much the correlation pattern deviates from that of [1] when conditions are no longer ideal.

2. Methods

The control subjects of the two case-studies presented here are both healthy individuals who, prior to recordings, had signed the informed consent form approved by the Institutional Review Board (IRB) of the University of Southern California. Surface Electromyography (sEMG) reduced-noise tripolar electrodes were placed at cervical (C2-C3), thoracic (T4-T6), lumbar (L3), and sacral (S2-S4) positions. The sensitive input prongs of the front-end electronics were aligned with the back muscle fibers [11]. The sEMG signals were amplified by an Insight Subluxation Station, Discovery model. The analog-to-digital conversion was done by a USB-1608FS card manufactured by Measurement Computing^{TM} and running on a Windows XP platform.

During Case Study I, 960,000 sample points of sEMG activity were recorded at a rate of 4 kHz as shown in Fig. 1. The analysis was performed during the first 120,000 samples because there is visual evidence that the signals burst synchronously at the beginning of the recording; this data segment is amplified in Fig. 2. This phenomenon of synchronicity of sEMG signals has also been observed on a different research subject [12].

The procedure for Case Study II was similar. Three seconds of data were analyzed using the same sampling rate as Case Study I. This data segment comprises a set of 12,000 samples, in which the bifurcation is present, as shown in Fig. 5.

We highlight the differences between the protocol of the earlier study [1] and the protocol utilized to collect the data of Case-Studies

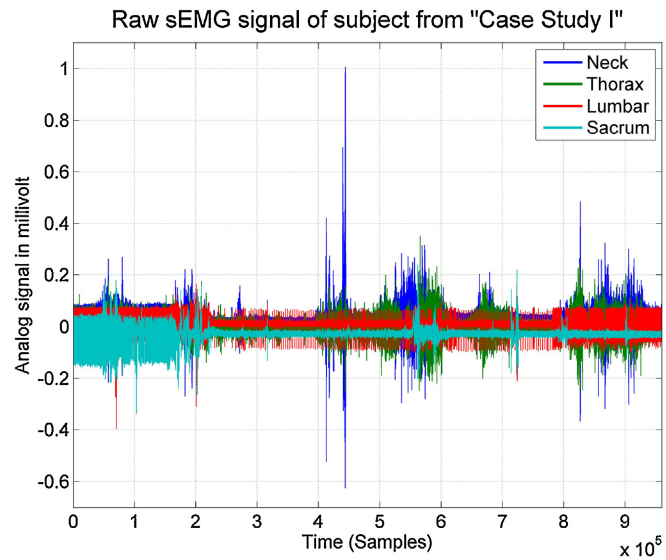

Fig. 1. Raw sEMG data at cervical, thoracic, lumbar and sacral positions of Case Study I.

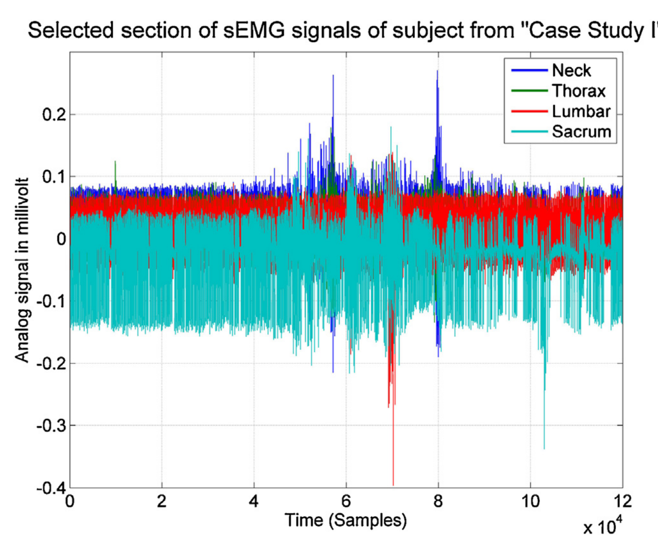

Fig. 2. Segment of first 120,000 samples from Case Study I at cervical, thoracic, lumbar and sacral positions.